Effectiveness of Transparent Shields in Protecting Explosive Operations Personnel

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ABSTRACT

The effectiveness of relatively portable, transparent shields for protecting personnel was evaluated for the unintentional reaction of explosives, propellants, and pyrotechnics in a laboratory setting. Measurements of blast overpressure, heat flux, and temperature were made at the head positions of a sitting operator, a standing operator, and a standing observer with the energetic materials placed at a comfortable position for hands-on operations on the other side of the shield. High-speed and video photography showed shield deflection from blast and the position of the most intense heat from detonating and burning energetic materials. After each test the shield was photographed and evaluated for fragment penetration, charring, and structural damage. Up to 11.7 g of explosive was detonated to simulate the probable event when handling primary explosives and the maximum event that could occur when handling secondary explosives. An explosive powder, a pyrotechnic, and a composite propellant (up to 244 g) were ignited and burned to simulate many of the incidents that could occur when handling unconfined energetic materials, except for primary explosives. The propelling charge in a 12-gauge shotshell, containing an 8 g cylinder of explosive instead of lead shot, was ignited with the shell confined in a simulated loading press. A flat, 20" wide sheet of polycarbonate (PC) with cutouts for arms and a commercial shield for chemistry laboratories were effective in protecting against blast overpressures not exceeding 2.3 psi from detonating charges $\leq$2 g. Since the blast wave reaching the operator comes around the shield, extending the sides of a flat shield away from the charge location, increasing the shield height to above the operator's head, and adding a top over the operator's head reduced the blast overpressures by a factor of three. A ½" thickness of PC was barely sufficient to stop the fragments from a 1/16" thick steel sleeve on a detonating 2.8 g charge. When detonating ~ 11.6 g charges, the shields had to be securely fastened at their base and top, and the bench they were mounted on had to be secured, to prevent the shield from striking the operator. The blast overpressures from the confined shotshell were less than that from 1.3 g detonating charges. The shields nearly totally protected the operator from heat and firebrands for even the largest (244 g) burning sample, a composite propellant.

INTRODUCTION

Transparent shields are used in some hands-on operations to protect personnel from blast, fragments, and heat associated with the accidental initiation of small amounts (typically <10g) of primary and secondary explosives, propellants, and pyrotechnics. Paragraph 8-3.1.4.a. of

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the Navy's explosive safety manual[1] specifies that, "In the absence of reliable data, the adequacy of these operational shields, including thickness, size, fastening and location, shall be proved by actual test with a minimum safety factor of 25% above the maximum expected charge before their use is permitted in operations." Paragraph 7-6.4. of the same reference specifies that shields are to be tested in accordance with Reference 2. Such testing was performed at White Oak since there was no documented data from similar testing at White Oak and very limited data from other explosive operating facilities.

Military Standard 398[2] specifies that the operator's head not receive more than a 2.3 psi peak positive incident pressure; that the upper torso be protected from incident and secondary fragments; and that the upper torso not be exposed to a thermal flux exceeding 0.62 $t^{-0.7423}$ cal/ cm^2 -s, where t is the exposure time in seconds. The effects of blast on personnel are summarized in Table 7-3 of Reference 1. Eardrum rupture occurs 1% of the time for an overpressure of 3.4 psi and 50% of the time at 16 psi. Lung rupture occurs at 10 psi for a pulse duration of 50 ms, and at 20-30 psi if the pulse duration is 3 ms. Thus, the maximum 2.3 psi overpressure allowed by reference 2 for an operator working behind a shield is below the threshold for disabling injury. The location of the operator's head is defined[2] to be 65" above the floor when standing and 31.5" above a chair seat when sitting. In addition to the blast pressure and heat flux measurements, still photographs of the shields are required before and after testing, and color cinematography at a rate of >400 frames per second is specified during the test.

Most tests were conducted to determine the protection offered by shields from detonating explosives, which would be the expected event from the accidental initiation of a primary explosive and would be the maximum credible event from any energetic material. Other tests were conducted to determine the protection that a shield offers from a pyrotechnic, a propellant, a cast explosive, and an explosive powder that burned, which is a likely event if the energetic material (other than a primary explosive) is unconfined and accidentally ignited. One test was conducted to determine the maximum event that could occur in a loading press for a 12-gauge shotshell containing an explosive sample for the JANNAF shotgun/relative quickness (SG/RQ) test. Since no guidance for designing the currently existing shields was available, pressure transducers at locations other than those required[2] were incorporated into the tests with detonating charges to determine the path of the blast waves that reach an operator. Also, barriers of various sizes were substituted for shields, and two tests were conducted with no barrier to obtain free-field measurements.

EXPERIMENTAL ARRANGEMENT

There is a wide variety of shield designs used at White Oak, but the majority of the shields are basically plastic plates that are mounted by a bracket to the bench. If the width of the shield makes reaching around it difficult, there are usually cutouts for the arms. The shields/barriers that were tested are summarized in Table 1. A drawing of Brazil's polycarbonate (PC) shield, which was used in many of the tests, is shown in Figure 1. Groves' PC shield was the same width as Brazil's shield but 10" higher. This shield was modified to reduce the blast pressure

to the operator as shown on the sketch in Figure 2. In Table 1, this shield is given the descriptor Wing2. Wing 1 is the same shield without the 1/4" thick PC top, and Groves' shield is the ½" thick PC plate without the side extensions and top. The shield in Table 1 with the descriptor of Double had ½" strips of Celotex near the side edges to maintain the air gap between Brazil's and Groves' shields, which were taped together. In two tests there was no shield/barrier to obtain free-field measurements of air blast from detonating charges. These measurements were useful for obtaining wave velocity and pressure for comparison with those in shielded tests.

The shields were mounted near the front edge of a 28" wide by 32" deep by 37" high table in a 10' x 16' x 8' high firing chamber. The table consisted of a steel angle frame with a 1" thick plywood top and a 1" thick plywood shelf at 15" above the floor. The table weighed <100 pounds and was not anchored to the floor. Following Test #18, 293.3 pounds of steel blocks were placed on the back edge of the table shelf. The location of the table was near the center of the firing chamber, so that there was at least 5' between the charge and the walls. The tops of the charges were typically 54" below the ceiling of the firing chamber. The distances from the charge to the walls and ceiling were large compared to the distances to an operator; thus, no reflected blast waves from walls or ceilings interfered with the incident blast wave to the operator. Furthermore, those reflected waves had greatly attenuated over the distances they propagated before reaching an operator. Since tables and benches in a laboratory are often located against a wall, a 3/4" plywood barrier the width of the table and extending 42" high was fastened to the back of the table after Test #4 to simulate a wall (Figure 4).

All shields, except a shield used in the chemistry laboratories, were mounted by two No. 404 C-clamps to the table. The Lab-Guard Model D-15-29PC shield, which is given the descriptor LabGard in Table 1, was mounted as it is in the chemistry laboratories. A 1/4" diameter aluminum rod was bent around the shield at a height of 13.5" above the table and each end was clamped to a horizontally-mounted ½" diameter rod, which simulated one rod of a lattice used for supporting glassware in the laboratory. The thumb screws on the clamps were finger tight to an average of 20 in-lb. In addition to the C-clamping of the other shields, the top of Wing2 was restrained by a 3/16" diameter, steel cable mounted to the back edge of the table top.

The detonating charges were PBXN-5 pellets of either ~2.6 g or ~11.5 g, except for two tests with 1.3 g cylinders of 1/4" thick Detasheet. Some of 2.6 g pellets, which were 0.50" diameter by 0.50" high, were fitted into either a 1/16" or 1/8" thick steel sleeve to generate fragments. All detonating charges were initiated by a Reynolds RP-80 detonator, whose 0.2 g of explosive is included in the following reporting of charge masses. The burning tests used a boron/ potassium nitrate (B/KNO_3) ignition mix, Class A RDX explosive powder, PBXN-103 explosive, and a composite propellant (FS-25-C) consisting of ammonium perchlorate and aluminum in an inert binder. Burning was ignited by an ICI Americas Inc. (formerly Atlas Powder Co.) M-100 electric match. The electric match was insufficient to ignite the explosives, even when embedded in them. For both the explosives and the composite propellant, 1 g of B/KNO_3 was used with the match as an ignition aid. A match was also used to replace the percussion primer in the shotshell test. The all-brass, 3" long shotshell was

loaded with a 2 g propelling charge of Olin Corp. WC 231 reloading powder and an 8 g sample of PBXN-103, the sample weight required for the SG/RQ test. A short ram that extended past the mouth of the shotshell was placed on the sample, and then a C-clamp between the base of the shell and the ram was used to axially confine the shotshell. This was an overtest of the confinement from the spring loaded ram used to seat the sample in the shotshell during loading.

The charge axis was located 7 to 8" from the shield, except for a reduced 5.5" when testing the 2.5" thick polymethylmethacrylate (PMMA) shield in Test #14. These distances represent a comfortable reach for an operator, but varied to maintain a consistent horizontal distance of 11.5" from the charge axis to the senors corresponding to an operator's head. All detonating charges were on a 4" square stand that was typically 2.5" high (3.5" high in Test #11, 4" high in Tests #10,21,22). Elevating the charges from the table reduced the damage to the table top; and in many practical applications, the charge is somewhat elevated from the table. For the burning tests, a 4" x 4" x 3/8" steel plate was placed on the wooden table top at the same position from the shield as in the detonating tests. The B/KNO_3 and RDX powders were put into a 50 mi plastic beaker that was placed on the steel plate. The height above the floor for the head of a standing operator was 65", as specified in Reference 2, and that for a sitting operator was 57". This height was based on several stool measurements plus the 31.5" specified above the stool seat.

The arrangement for the instrumentation for the first three tests in shown in Figure 3. Transducers G1-5 were Atlantic Research Corp. Model LC-33 pencil gauges for measuring side-on air blast; these gauges are no longer manufactured. Transducer G3 corresponds to the head position of a standing operator; and in subsequent tests, G5 was moved to 8" below G3 to correspond to the head position of a sitting operator. Transducer G2 corresponds to the head position of an observer that is standing at the right shoulder of the operator, and G 1 corresponds to the head position of a more distant observed In the following presentation of data, the reported measurements for an observer are from G2. G2 and G4 are the same distance from the charge as are G1 and G5. G4 and G5 were pointed directly at the charge for normal orientation to the blast wave; however, transducers behind the shield were horizontally oriented because the direction of the approaching blast wave was not known a priori.

In addition to the pressure transducers locations shown in Figure 3, the positions of two thermocouples are designated. T1 was mounted on the front side of the shield, while T2 was positioned near the head of a standing operator. Both were chromel/alumel thermocouples made from 0.002" wire, having a response time of probably >l ms in a convective atmosphere. These thermocouple signals were amplified to 10 mv/^{0}C. After Test #5, T1 was removed to preserve it from being cut by fragments. After Test #16, a multiple sensor probe (MSP) was positioned midway between the head positions of a standing and sitting operator. T2 was incorporated into the MSP along with a copper-constantan circular foil heat-flux gauge, also known as a Gardon gauge)[3]. Two Gardon gauges from Thermogage Inc. were used in the MSP. The gauge in Tests #17-21 had a 1 mm diameter foil and a corresponding

response time of 100 ms, which would have been the state of technology at the time when the shield testing standard[2] was written. The Gardon gauge in Test #22 had a 1/8 mm foil diameter and two orders of magnitude faster response time. Since much of the energy from detonating charges goes into compressional work on the surrounding environment, heat flux was expected to be significant only for the deflagration of pyrotechnics and the burning of secondary explosives and propellants, for which a 100 ms response time is appropriate.

The pressure instrumentation changed somewhat throughout the testing. After Test #3, G5 was moved to the head position of a sitting operator. G4 was moved to a position that was 8" to the left of G3 in Test #5 and in subsequent tests was lowered 8" to be to the left side of the head position of a sitting operator. The off-center locations of G4 helped to determine the path of the blast waves that reached an operator as well as showed the effect of not being positioned in the center of the shield. In another variation, G1 in Tests #15,16 was positioned under the transducers for the standing and sitting operator at the same height as the charge for detecting the blast wave transmitted through the shield and that which passed through the cutouts for arms. As will be discussed, the primary blast wave arrived at those transducers from around the shield, and only a weak wave was transmitted through the shield. Even though the blast wave did not propagate parallel to the axis of those transducers, which is how they are intended to be used in measuring side-on overpressure, simultaneous wave arrival from several directions normal to the transducer axis was still a side-on loading. The blast wave measurements were verified by horizontally mounting another style of transducer (PCB 102A) in the MSP. This transducer would view waves coming from the sides and top of the shield as side-on measurements, thus providing a comparison to the response of the pencil gauges.

Figure 4 shows the arrangement of the instrumentation, which includes the MSP for the detonation of 1.3 g charges in front of Brazil's shield (Tests #17,18). Transducers G1-3 are in the same location as in Figure 3, while G4-5 have been moved behind the shield as discussed above. Whereas Figure 3 shows the distance from G3 to the top edge of the shield as 8" and the distance to the front of the shield to the charge axis as 8", the combined horizontal distance from G3 to the charge axis is only 11.5" as shown in Figure 4, because the shield leans at an angle of 180 from the operator (Figure 1).

The pressure transducer and thermocouple signals for all tests were recorded on magnetic tape, which had to be analyzed elsewhere. Since the data was generally not available until several days after the test, most signals were also simultaneously digitized on a LeCroy Model 8013A transient recorder after the Test #9. The LeCroy recorder was interfaced with a computer that provided reduced data immediately after the test. The heat-flux signals, because of their low sensitivity, were recorded on a Nicolet 2090 oscilloscope with a Model 201 plug-in having a full-screen range of ±10 mv. Reported times are relative to the firing signal to the detonator, which would require only microseconds to initiate. Cinematography from one side of the shields was obtained with a Photo-Sonics, Inc. Model PL pin registered camera operating at 500 frames/ second with a 0.5 ms shutter time. Kodak 7250 film (ASA 400, tungsten color balance) was used with the arrangement illuminated by two 1000 Watt quartz lamps. A video camera viewed the other side of the shield. Photographs of the mounted

shields were taken before and after the tests.

EXPERIMENTAL RESULTS

A summary the times of blast wave arrival (ta) and peak blast overpressure (p) at the head positions of a standing operator, sitting operator, and standing observer are listed in Table 2 for the detonating charges and the exploding shotshell. The values of p are associated with the first or primary wave; reflected or secondary waves were of lower but often significant amplitude. The secondary waves were not as reliably measured by the pencil gauges because of errors associated with disturbance by the primary wave of the mounts for the transducers and their high-impedance cables. This was observed by changing the mounting arrangements of the pencil gauges and comparing their output with the measurements from the PCB 102A transducer, which has a low impedance cable. The response of this transducer in the MSP to the primary blast wave was basically an average of the responses from the pencil gauges located 4" above and below it at the head positions of a standing and sitting operator, respectively; although, the MSP transducer trace was more characteristic of that from the pencil gauge above it. This verifies that the pencil gauges had reasonably recorded the overpressures even though the gauges were not oriented normal to the blast wave propagation, as will be discussed.

Pressure-time (p-t) records from selected tests at the head position of a standing and sitting operator are shown, respectively, in Figures 5 and 6. The primary waves behind the shield were very complex, being the composite of multiple waves arriving at the transducers nearly simultaneously. Especially at the head position of the standing operator, two major peaks were sometimes associated with the primary blast wave, as listed in Table 2. Increasing the charge size from 1.3 to 2.8 to 11.5 g in front of Brazil's shield (Figures 5D, 5B, 5E, respectively) or protecting the operator with a different shield for the same charge size (comparing Figures 5B and 5C for 2.8 g charges in front of Brazil's and Labgard shield and comparing Figures 5E and 5F for 11.6 g charges in front of Brazil's and Wing2 shield) changed the p-t traces at the head position of a standing operator. Relative to an unconfined 2.8 g charge in Tests #1,3,5, (e.g., Figure 5B) increasing the charge mass to 3.0 g in Test #2 or confining the charge in Tests #6,7,10,11 also significantly changed the p-t profiles. Confining the charge increased the amplitude of the first wave and decreased the amplitude to the second wave. Also, the two waves were distinct for the confined charges, compared with the connected waves for the unconfined 2.8 g charges. While multiple waves are evident in the p-t traces for the primary blast to reach the head position of a sitting operator (Figure 6), these waves arrive nearly simultaneously, resulting in a broad pulse compared to the free-field (no shield) measurement in Figure 6A.

When a transducer was positioned just behind the shield at charge height, an overpressure of 0.8 psi was recorded for the barrier without arm cutouts in Test #15 versus 2.8 psi for a shield with arm cutouts in Test #16. While some of the difference is attributable to the different widths of the barrier and shield, much of the increased overpressure in Test #16 is due to the cutouts. As shown in Table 2 for Test #16, the overpressures at the position of a standing and sitting operator were only about half of the 2.8 psi measured at charge height. Prior to the

peak in both tests, there was an earlier wave of insignificant pressure that was associated with direct transmission of blast through the shield.

Free-field measurements at various distances from detonating 2.8 g charges were obtained in Tests #1,3,8,9. In Tests #1,3, the reflected wave from the shield had almost caught the first wave recorded at the far transducer (GS) in front of the shield, whereas the two waves had coalesced for the slightly larger 3.0 g charge in Test #2. In Tests #8,9, the pressure profiles were less complex (e.g., Figure 6A) than in the shield tests and more typical of blast waves observed in field tests at a large number of radii from the charge. However, the response of G3 at the head position of a standing operator in Tests #8,9 (Figure 5A) was an unrealistic two pulse waveform because the transducer axis was at too large of an angle (65°) relative to the path of the blast wave. When plotting transducer locations versus arrival times from the free-field measurements, the average wave velocity was 365 m/s. This velocity was used to predict arrival times of the blast wave to the transducer by various paths for comparison with the measured values in Table 2.

In Test #6 and 7, the ½" thick PC shield stopped all fragments, but several fragments from the 1/16" sleeves nearly exited the backside. By comparison, the 3/4" plywood sheet that simulated a wall at the back of the table had numerous holes through it from fragments. In these tests, the primary fragments struck the shield at the charge height (2.5 to 3.0") above the table, where the shield is backed by a wooden wedge (Figure 1). In Test #10 the base of the charge was raised to 4" so that the primary fragments would strike a section of the shield not backed by the mounting arrangement. The fragments did not penetrate any further. Next to the simulated back wall in this test, a large coffee can with a pair of safety glasses taped on the outside was filled with water to simulate an operator's head. The glasses and can were penetrated by several fragments. The PC lenses, just like the shield, had little peripheral damage beyond the small hole through which the fragment passed. The damaged zone appeared as though a hot object had melted through the plastic. One of the larger fragments that was recovered intact had a mass of only 80 mg. By contrast, the larger fragments produced from the thicker sleeve in Test #11 had just begun to enter the front surface of the shield.

Essentially no measurable temperature increase ΔT was recorded from the detonating charges at a position between the head of a standing and sitting operator, although there was a bright momentary flash which was too fast for either the thermocouples or heat flux sensors to respond to. The only measurable heat flux was from the 11.7 g charge in Test #20; a peak flux of 0.1 cal/cm^2-s was obtained at 18 ms from the sensor with the 100 ms response time. The much faster sensor did not record any heat flux from the 2.8 g charge in Test #22. The high-speed films verified that all of the flame remained in front of the shield, except for the two ~11.6 g charges, where some flame came back through the arm holes. In a real accident, these passages would have been mostly blocked by the operator. On the front surface of Brazil's shield (i.e., unprotected surface closest to the charge), ΔT from 80 to 120 ^{0}C occurred at times ranging from 20 to 60 ms after the detonation of ~2.8 g charges in Tests #1-3,5. In Test #4 with a 11.5 g charge, ΔT on the front of the shield went off-scale at 200 ^{0}C. This verifies

the shielding of the operator from the hot detonation products, since the same instrumentation was used on both sides of the shield.

The C-clamp mounting of the shields was satisfactory and there was only minor (il/2") displacement of the top of the shields from ≤3.0 g charges. A similar deflection is easily achieved by hand pressure on the top edge of these shields. The 11.5 g charge in Test #4 caused large shield deflection in addition to translating the table to which the shield was mounted. The high-speed photographs showed that the shield struck twice the transducer corresponding to the head of a sitting operator For the Wing2 shield subjected to a 11.7 g charge in Test #20, there was ~l" deflection at the top of the shield. As noted in the previous section for this test, the table was weighted and the top of the shield was restrained by a cable. The bottom of the LabGard shield did move ~2" toward the operator in Test #22.

In the exploding shotshell test, the brass shell broke into several pieces from the interior pressure associated with the combusting WC 231 powder. The 8.0 g PBXN-103 sample was recovered intact with no indication of damage, and was subsequently used in a burning test. The blast overpressures listed in Table 2 from the 2.0 g of powder were less than those from a detonating 1.3 g charge in front of the same shield (Tests #17,18).

The shields, types of energetic material, and their amounts used in burning tests are listed in Table 3. No significant overpressures (>0. 1 psi), nor any significant temperatures nor heat fluxes, were recorded at the position of the operator. The video camera showed the flame and heat going primarily up, and no flame came around the sides of the shields or over the top. Except for Tests #23,24 with B/KNO_3, the burning required seconds to complete. The front surface of the PC shield was charred and pitted near its base after Tests #30,31 with the composite propellant, and the shield was warm to the touch afterwards, but otherwise in usable condition. Most of the damage from these two tests was due to at least one piece of burning propellant being ejected from the original site, striking the shield, and then burning at the base of the shield. Without the shield, the clothing of the operator would have probably been set afire. There was considerably more charring to the wooden table top than the shield. After burning 50 g of RDX in front of the Lab-Guard shield in Test #34, it was only necessary to clean some soot from the shield with a tissue.

DISCUSSION

The overpressures to a standing and sitting operator from various unconfined charges in front of Brazil's shield are plotted in Figure 7. The fits through the data points are only for the purpose of interpolation. Dissimilar fitting functions were required because different waves superimpose at each operator position, as discussed below. For charge masses ≤2.8 g, however, a linear function passing through the origin is sufficient to represent both data sets. A 2.0 g charge satisfies the 2.3 psi limit for both a standing and sitting operator. The maximum 2.3 psi overpressure permitted at the operator's head, whether sitting or standing, was not exceeded for Test #11 with a 1/8" sleeve around the explosive. The thinner 1/16" wall sleeve also reduced the measured blast pressures, but not by as much as the thicker sleeve.

There was a significant reduction in blast pressure to <2.3 psi from both confined and unconfined 2.8 g charges if a standing observer was positioned just 12.5" behind and 5', to the side of an operator.

The various tests revealed the paths of the blast waves to the operator. The impedance difference between a plastic or glass shield and air would dictate that little blast pressure would be transmitted by the shield. This was verified in Test #13 with the Double shield and in Test #15, in which a transducer at charge height behind the shield recorded an insignificant wave associated with direct transmission. Also, for any of the shielded 2.8 g charges, t_a for the first wave was too long if it had arrived by transmission through the shield when comparing t_a from the free-field tests. The arrival time of blast waves from unconfined 2.8 g charges at the head position of a standing operator behind the taller shield of Groves in Test #12 when compared with Brazil's shield in Test #5 (Figure SB), revealed that first wave (t_a = 1.2 ms) came over the top of Brazil's shield. Also, the first wave (t_a= 1.2 ms) in Test #14 for a 26" wide by 26" high PMMA shield did not exist in Test #15 on a similar width shield that was much higher. While the amplitude of the first wave from an unconfined 2.8 g charge was $\leq$1.5 psi for Brazil's shield, it was a long duration pulse on which the second wave was superimposed. In Test #5, as shown in Figure 5B, the first wave had declined to 0.8 psi by the arrival of the second wave (t_a= 1.7 ms). If the first wave had been eliminated, the second wave would have had an amplitude of ~2.7 psi, as did the t_a = 1 6 ms wave in Test #12. This ~2.7 psi and the remaining ~0.8 psi from the first wave nearly add to the 3.6 psi peak for the second wave in Test #5.

The waves with t_a = 1.6 to 1.7 ms arriving at head of a standing operator, which is the second wave for Brazil's shield and the first wave for Grove's shield, had come around the shields. The side wave was predictably delayed to 1.9 ms by increasing the shield width to 26" in Test #14 and 25" in Test #15. Since blast pressure is attenuated simply by increasing the distance through the air from the charge to the operator, side extensions were added to Groves' shield, as shown in Figure 2, to make Wing1 and its variation Wing2. The relatively minor modification resulted in an overpressure for a sitting operator that was just below the 2.3 psi limit for a 11.7 g charge.

The ability of the shields to attenuate blast is depicted on the pressure-distance plot in Figure 7. The distances around the side of the various shields to a sitting operator are listed in Table 1. When comparing free-field (8.0 psi at the position of a sitting operator) and shielded measurements for 2.8 g charges, all shields offer significant attenuation of the blast wave that is enhanced with increased shield width. The attenuation of the blast wave occurs from both the increased path length to the operator and from the blast wave turning a corner. The overpressures behind Brazil's shield and Wing2 from an ~11.6 g charge are less than from an unshielded 2.8 g charge. The fits through the data for the various charge masses should not extrapolated. The fits in Figure 6 for the three charge masses can be approximated by

$$p\ (\text{psi}) \simeq 11.2\ m^{0.5}\ e^{-0.007x},$$

where p is the overpressure, m is the charge mass in grams, and x is the distance from the

charge in inches.

CONCLUSIONS

The relatively simple shield design of Brazil and the commercial Lab-Guard shield are only effective for protecting against blast overpressure from small ($\leq$2 g) detonating charges. Blast overpressure to the operator came from around the shield versus direct transmission through the shield. Simply increasing the width and height of the shield, even with the cutouts for arms, greatly reduced the blast overpressure to the operator. Clamping the shields at only their base on an unanchored table was sufficient to prevent the shields from impacting the operator for charge masses $\leq$3.0 g, whereas the top of the shield had to be restrained and the table weighted or anchored for ~11.6 g charges. A shield of ½" PC was nearly penetrated by some of the fragments from 1/16" thick steel sleeves around 2.8 g charges. Larger charge weights will require more shield thickness to protect against fragments. The shields nearly totally protected the operator from heat and direct contact with burning material for even the largest (11.7 g) detonating charge and the largest (244 g) burning charge. Obviously, shield protection only pertains to the parts of the operator's body behind the shield, and protection for hands and forearms must still be considered. While these results provide some guidance in developing a shield, it should still be tested with a minimum safety factor of 25% above the maximum expected charge.

REFERENCES

l. NAVSEA OP-5, Vol. 1, 5th Rev.; Ammunition and Explosives Ashore; Safety Regulations for Handling, Storing, Production, Renovation and Shipping

2. Military Standard 398; Shields, Operational for Ammunition Operations, Criteria for Design of and Tests for Acceptance

3. American Society for Testing and Materials Standard E511-73; Measurement of Heat Flux using a Copper-Constantan Circular Foil, Heat Flux Gage

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Table 1. Description of Shields

Descriptor in Table2	Dimensions+ W (in)	H (in)	T (in)	Mat'l*	D^ (in)	Comments#
None	-	-	-	-	20.75	Free-field measurements
Bazil	20	24	1/2	PC	29.0	18^{o} tilt from operator, 4 1/4" wide x 7 3/4" high cutouts for arms
Groves	20	34	1/2	PC	28.2	8" high x 2" wide cutouts for arms
Double	20	34	1 1/2	PC	-	Bazil's shield mounted in front of Groves' shield with 1/2" air space between them and flush at the top
26x26	26	26	2 1/2	PMMA	-	3^{o} tilt from operator
25x49	25	49	1/2	PC	37.2	
Wing1	33	34	1/2	PC	42.4	Groves' shield with side extensions of 1/4" PC angled 35^{o} toward operator
Wing2	33	34	1/2	PC	42.4	Wing1 with 1/4" PC top
LabGard	15	29	1/8 PC+1/4 PMMA		26.5	Lab-Guard Model D, semi-circular PC shield with weighted base and PMMA liner

+ W = width, H = height, T = thickness

* PC = polycarbonate, PMMA = polymethylmethacrlylate

^ D = minimum distance from charge to head position of a sitting operator (distance around side of a shield)

Shields vertically mounted unless otherwise noted

Table I. Description of Shields

Table 2. Summary of Blast Times of Arrival and Overpressures Behind Shields at the Head Position of a Standing Operator, Sitting Operator, and Observer for Detonating Charges and an Exploding Shotshell

Test	Shield	Charge Size & Mass/ Confinement, if any	Standing Operator t_a (ms)	Standing Operator p (psi)	Sitting Operator t_a (ms)	Sitting Operator p (psi)	Observer p (psi)
#1	Bazil	0.5" dia. x 0.5", 2.8 g	1.2, 1.6	1.0, 3.7	N/A	N/A	1.1
2	Bazil	0.5" dia. x 0.5", 3.0 g	1.1, 1.7	1.3, 3.2	N/A	N/A	1.3
3	Bazil	0.5" dia. x 0.5", 2.8 g	1.2, 1.7	1.5, 3.5	N/A	N/A	1.7
4	Bazil	1.25" dia. x 0.35", 11.5 g	0.8	9.2	0.9	5.0	4.2
5	Bazil	0.5" dia. x 0.5", 2.8 g	1.2, 1.7	1.5, 3.6	1.1	2.5	2.0
6	Bazil	0.5" dia. x 0.5", 2.8 g 0.628 O.D. steel sleeve	1.1, 1.6	2.1, 1.2	1.1	2.3	1.3
7	Bazil	0.5" dia. x 0.5", 2.8 g 0.628 O.D. steel sleeve	1.0, 1.6	2.3, 1.5	1.1	2.2	1.5
8	None	0.5" dia. x 0.5", 2.8 g	1.0	N/A**	0.7	8.0	3.7
** Transducer axis at too great of an angle relative to direct line to charge for valid data							
9	None	0.5" dia. x 0.5", 2.8 g	1.0	N/A**	0.7	8.0	3.6
10	Bazil	0.5" dia. x 0.5", 2.8 g 0.626 O.D. steel sleeve	0.9, 1.5	3.0, 1.1	1.0	1.9	1.9
11	Bazil	0.5" dia. x 0.5", 2.8 g 0.754 O.D. steel sleeve	0.9, 1.7	1.9, 0.9	1.0	1.6	1.3
12	Groves	0.5" dia. x 0.5", 2.8 g	1.6	2.7	1.3	2.9	1.6
13	Double	0.5" dia. x 0.5", 2.8 g	1.7	2.6	1.3	2.9	1.7
14	26x26	0.5" dia. x 0.5", 2.8 g	1.2, 1.9	1.2, 1.2	1.5	1.9	1.1
15	25x49	0.5" dia. x 0.5", 2.8 g	1.9, 2.4	1.4, 1.2	1.6	1.5	1.1
16	Wing1	0.5" dia. x 0.5", 2.8 g	1.9, 2.1	1.0, 1.4	1.3	1.0	1.1
17	Bazil	0.5" dia. x 0.25", 1.3 g	1.3, 1.7	1.1, 1.7	1.2	1.5	1.2
18	Bazil	0.5" dia. x 0.25", 1.3 g	1.3, 1.7	0.9, 1.8	1.2	1.3	1.2
19	Wing2	0.5" dia. x 0.5", 2.8 g	1.9, 2.3	0.8, 1.2	1.3	1.2	1.1
20	Wing2	1.25" dia. x 0.35", 11.7 g	1.4, 2.0	0.9, 3.1	1.4	2.1	3.0
21	LabGard	0.5" dia. x 0.25", 1.3 g	1.4	1.7	1.3	1.6	0.8
22	LabGard	0.5" dia. x 0.5", 2.8 g	1.2	3.1	1.2	3.0	1.9
25	Bazil	Shotshell, 2.0 g powder	7.9	1.1	7.5	0.8	0.6

Table 2. Summary of Blast Times of Arrival and Overpressures Behind Shields at the Head Position of a Standing Operator, Sitting Operator, and Observer for Detonating Charges and an Exploding Shotshell

Table 3. Description of Burning Tests

Test	Shield	B/KNO_3 Ignition Aid	Test Material
#23	Bazil	None	B/KNO_3, 3.0 g
24	Bazil	None	B/KNO_3, 10.0 g
29	Bazil	1.0 g	PBXN-103, 8.0 g
30	Bazil	1.0 g	FS-25-C composite propellant, 50 g
31	Bazil	1.0 g	FS-25-C composite propellant, 255 g
33	Bazil	1.0 g	Class A RDX powder, 10.0 g
34	LabGard	1.0 g	Class A RDX powder, 50.0 g

Table 3. Description of Burning Tests

Figure 1. Brazil's Polycarbonate Shield

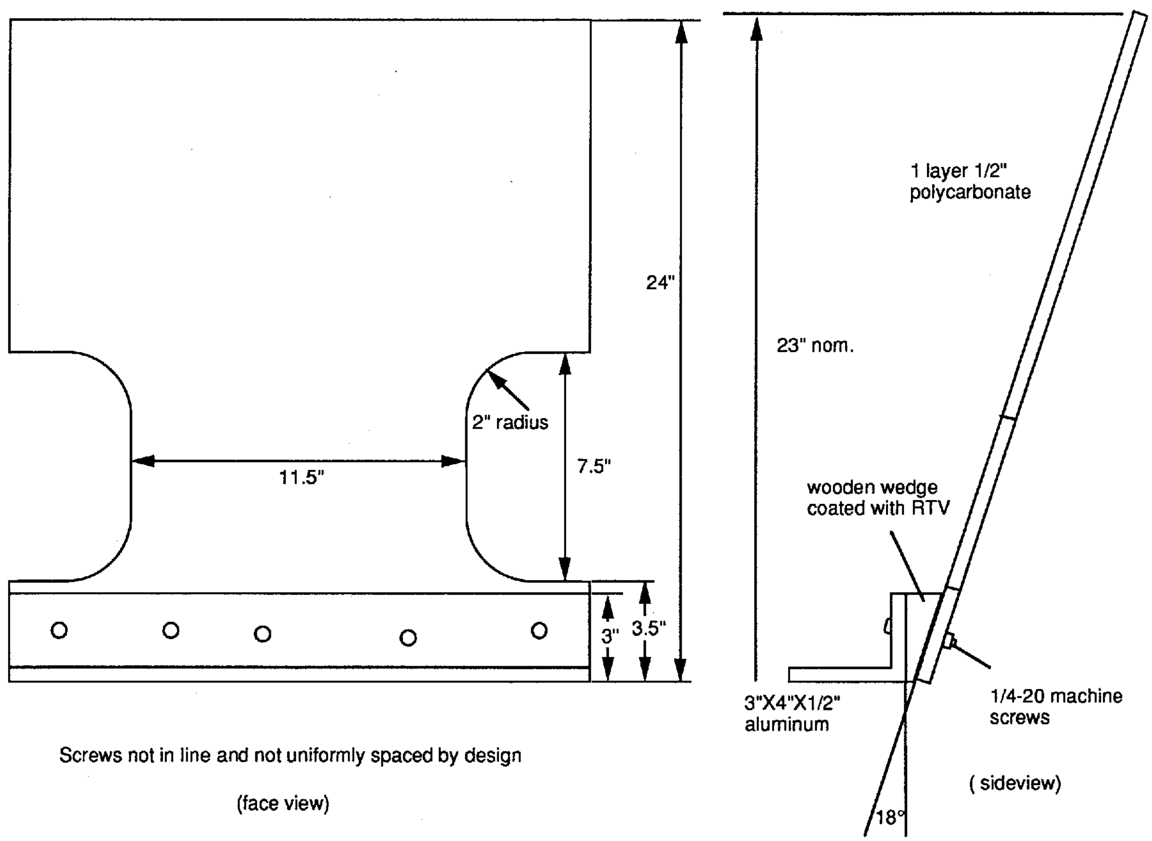


Figure 1. Bazil's Polycarbonate Shield.

Figure 2. Polycarbonate Shield with Side Extensions and Top (Wing2)

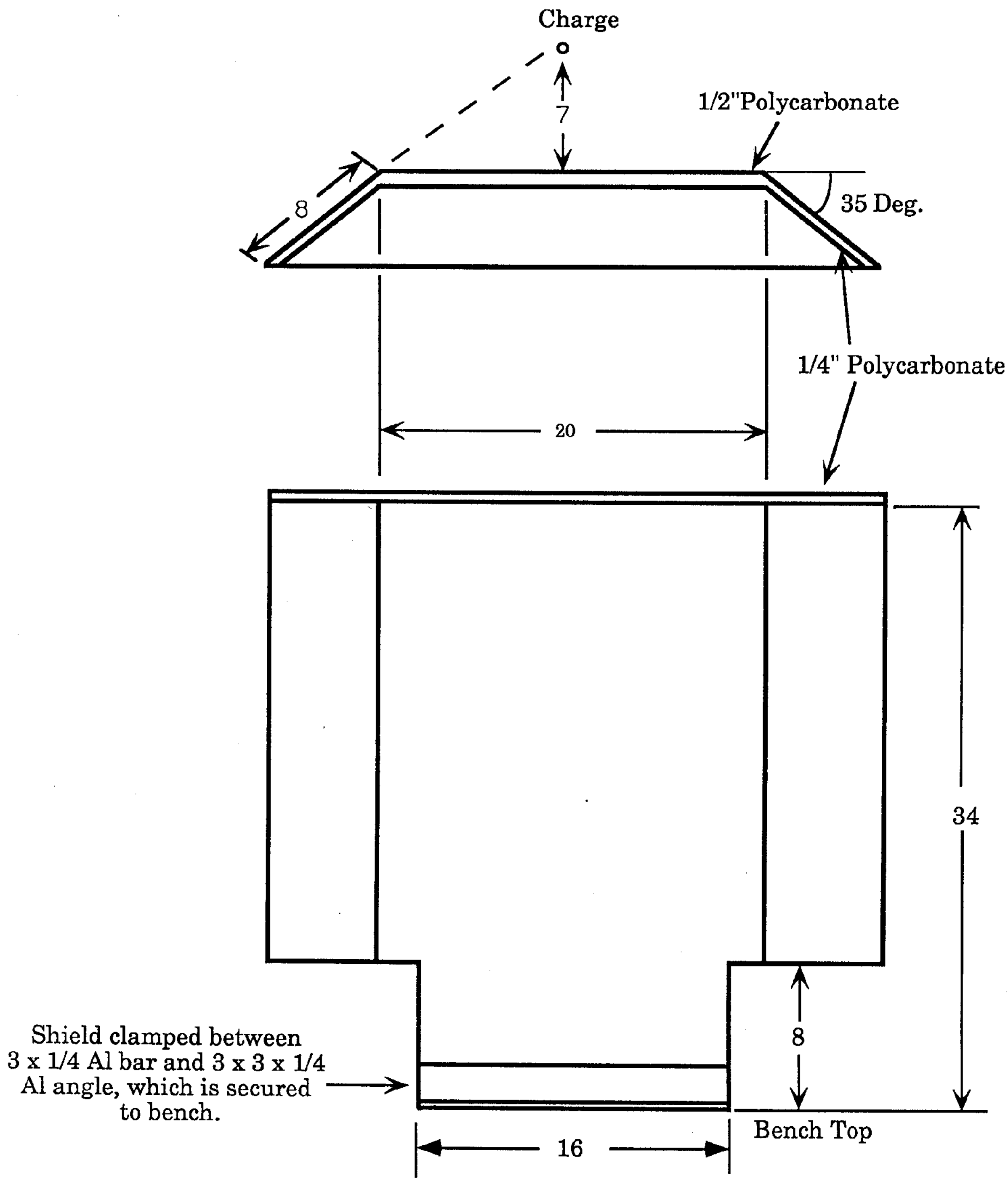
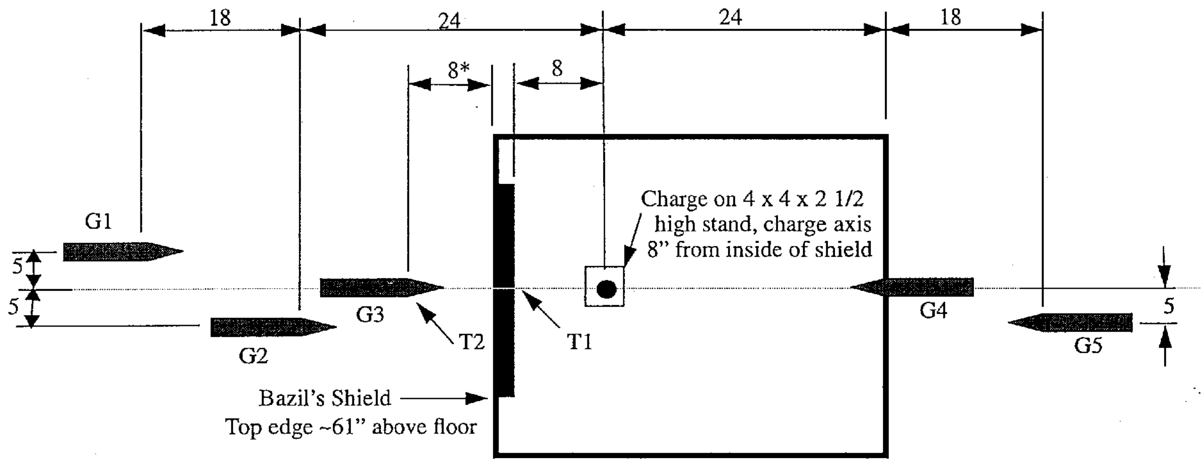


Figure 2. Polycarbonate Shield with Side Extensions and Top (Wing2)

Figure 3. Firing Chamber Arrangement for Shield Tests #1-3



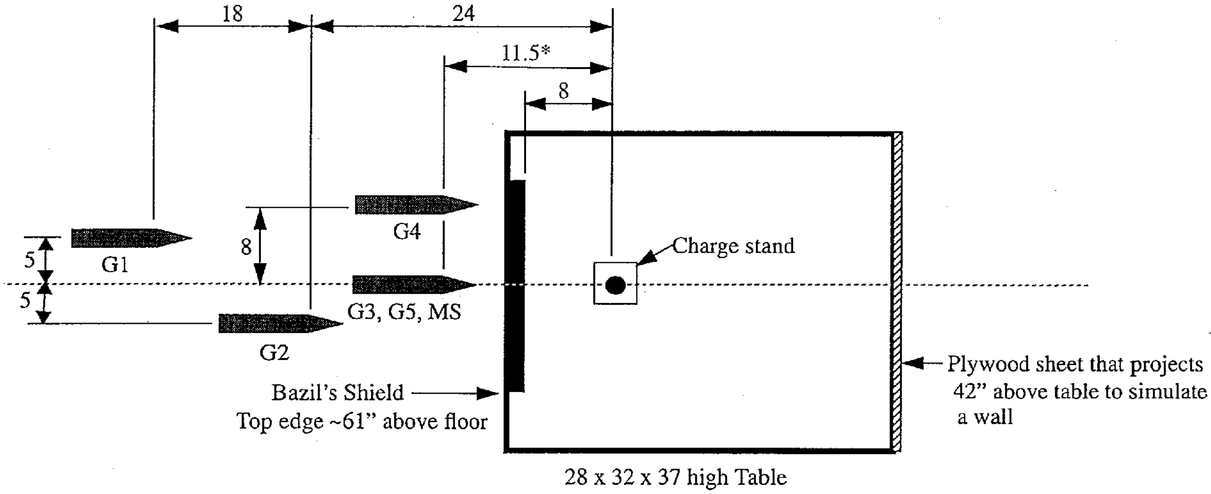
All dimensions in inches

T1, T2 are chromel/alumel thermocouples of 0.002 wire; T1 mounted on inside of shield at 8.8" above table; T2 mounted below and near G3

 PCB Model LC-33 pencil gauges for side-on air blast at 65" above floor level
Gauge locations relative to sensing area at 3 1/2" beyond the tip
G1-3 mounted horizontally; G4,5 pointed at charge
*G3 at head location, mounted 8" from top edge of shield, which leans from vertical by 18 degrees

Figure 3. Firing Chamber Arrangement for Shield Tests #1-3

Figure 4. Firing Chamber Arrangement for Shield Tests #17-#18



All dimensions in inches

MS is a multiple sensor mounted between G3 and G5 that incorporates a chromel/alumel thermocouple of 0.002 wire, a PCB 102A pressure transducer, and a Thermogage circular foil heat flux gauge

G1-5 PCB Model LC-33 pencil gauges for side-on air blast

Gauge locations relative to sensing area at 3 1/2" beyond the tip

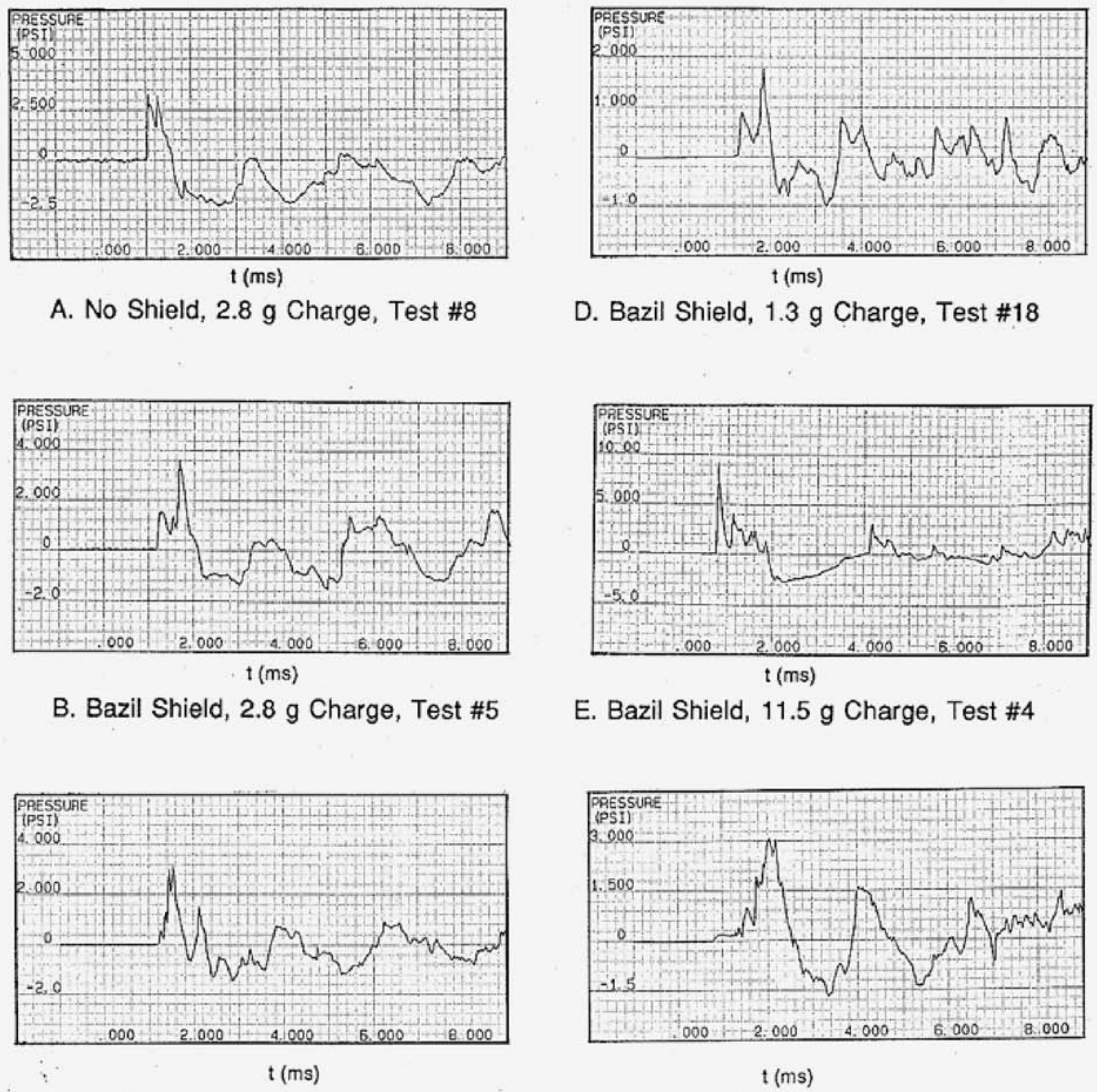
All gauges mounted horizontally

G1-3 at 65" above floor; G4,5 at 57" above floor

*G3 at head location, mounted 8" from top edge of shield, which leans from vertical by 18 degrees

Figure 4. Firing Chamber Arrangement for Shield Tests #17 and #18

FIGURE 5. Blast Overpressure at Head Position of Standing Operator With and Without Shielding From Various Detonating Charges



A. No Shield, 2.8 g Charge, Test #8

D. Bazil Shield, 1.3 g Charge, Test #18

B. Bazil Shield, 2.8 g Charge, Test #5

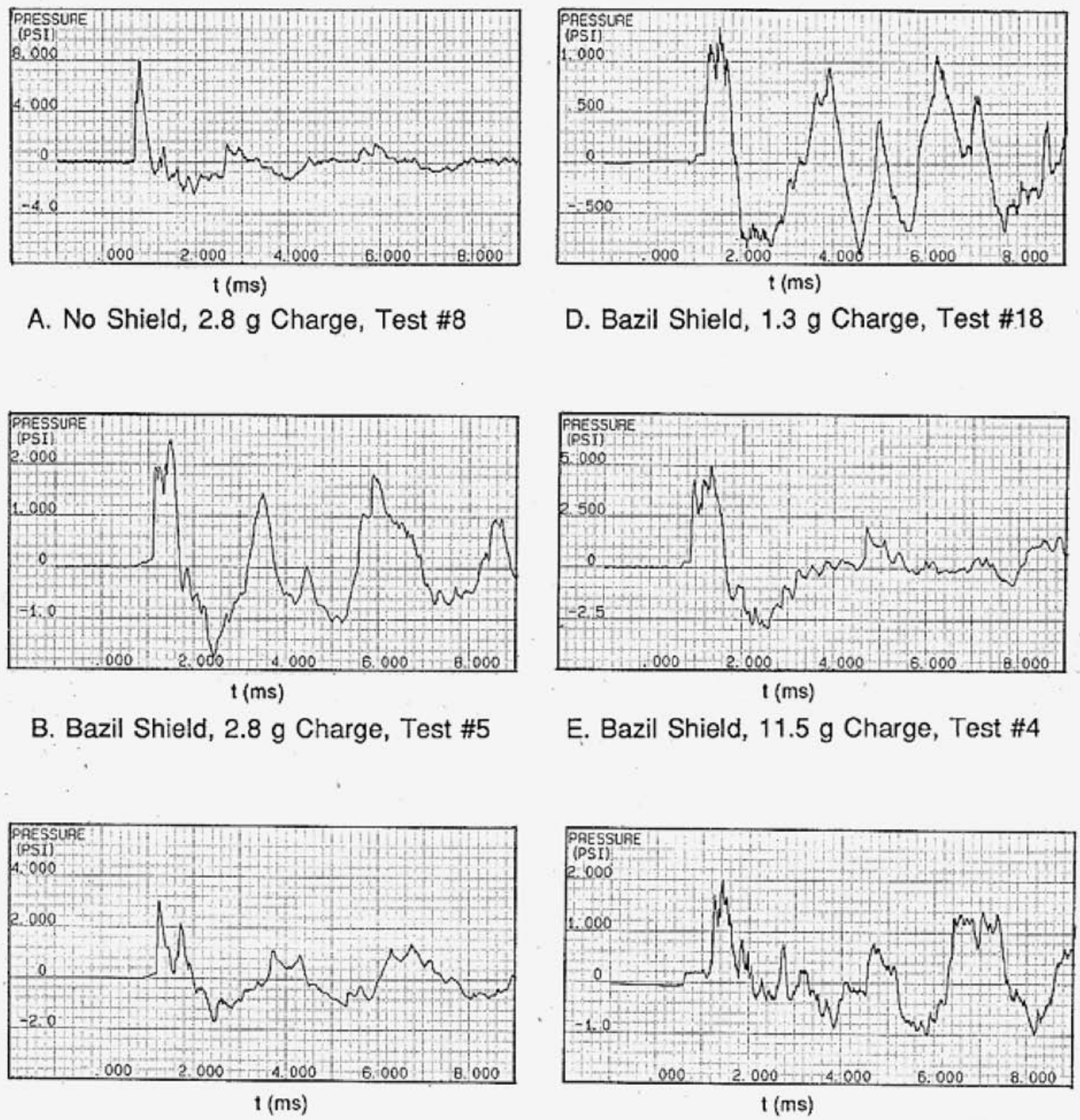
E. Bazil Shield, 11.5 g Charge, Test #4

C. LabGard Shield, 2.8 g Charge, Test #22

F. Wing2 Shield, 11.7 g Charge, Test #20

FIGURE 5. Blast Overpressure at Head Position of Standing Operator With and Without Shielding From Various Detonating Charges

FIGURE 6. Blast Overpressure at Head Position of Sitting Operator With and Without Shielding From Various Detonating Charges



A. No Shield, 2.8 g Charge, Test #8

D. Bazil Shield, 1.3 g Charge, Test #18

B. Bazil Shield, 2.8 g Charge, Test #5

E. Bazil Shield, 11.5 g Charge, Test #4

C. LabGard Shield, 2.8 g Charge, Test #22

F. Wing2 Shield, 11.7 g Charge, Test #20

FIGURE 6. Blast Overpressure at Head Position of Sitting Operator With and Without Shielding From Various Detonating Charges

Figure 7. Blast Overpressures Behind Brazil's Shield from the Detonation of Unconfined Charges

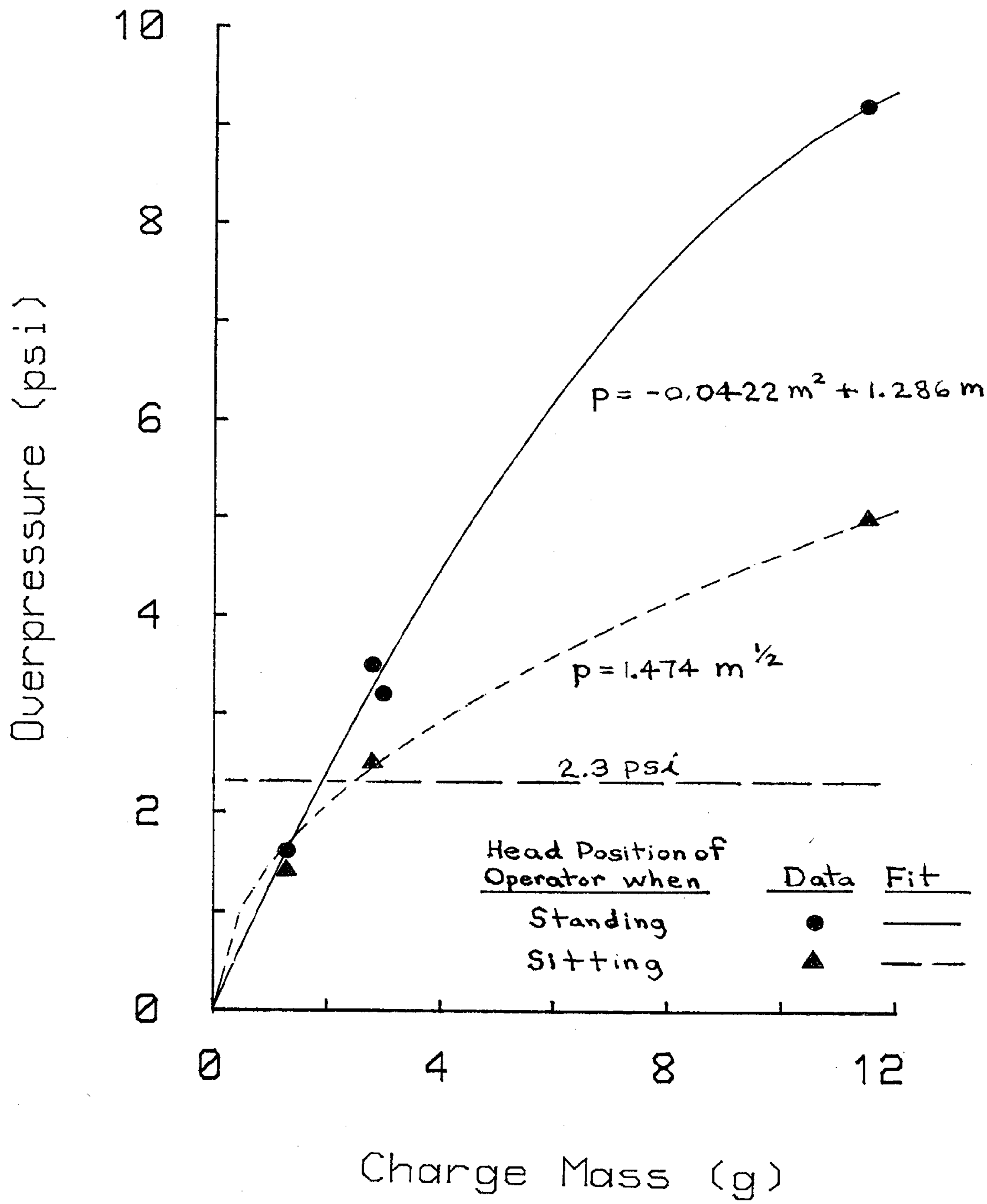


Figure 7. Blast Overpressures Behind Bazil's Shield from the Detonation of Unconfined Charges

Figure 8. Blast Overpressure for a 2.8 g Charge Without Shielding and from ~11.6 to 1.3 g Charges for a Sitting Operator Behind Various Shields

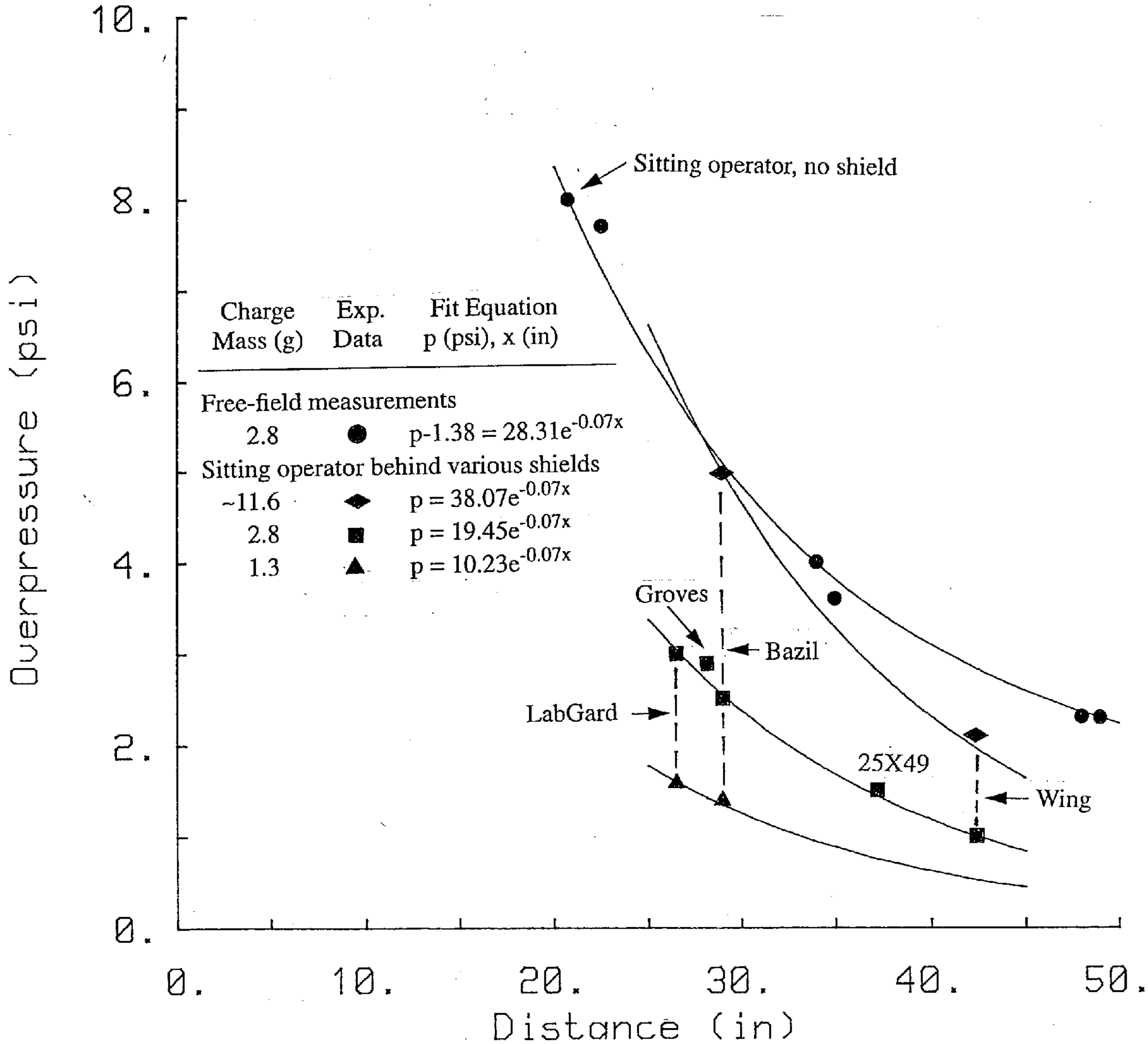


Figure 8. Blast Overpressures for a 2.8 g Charge Without Shielding and from ~11.6 to 1.3 g Charges for a Sitting Operator Behind Various Shields